A Robust Spatial Acquisition Algorithm for Extended Source using Subpixel Image Scanning

Shinhak Lee and Tsun-Yee Yan
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive, Pasadena, CA 91109

Abstract

We present a new spatial acquisition algorithm using subpixel image scanning. Extended source spatial acquisition is the process of determining the position of the extended source. Conventional methods for the Sun illuminated Earth image include the correlation and the edge extraction method. The required acquisition accuracy for deep space optical communications is on the order of $1/20^{th}$ pixel to effectively establish a communication link. The simulation results show that the acquisition accuracy on the order of $1/40^{th}$ pixel can be achieved with step size of $1/5^{th}$ pixel in scanning while the conventional methods are limited to $1/10^{th}$. The new algorithm also shows significant improvement in noise sensitivity.

1. Introduction

NASA/JPL has initiated a technology development program to explore laser communications for deep space applications. The purpose is to increase the information return capability by at least an order of magnitude while reducing the size of the spacecraft. The inherent advantages of laser communication over traditional RF communications lie on the fact that shorter operating wavelength requires significantly smaller aperture. For spaceborne systems, this translates to smaller beam divergence and hence the reduction in size and mass of the communication system. The overall system cost could also be reduced by a significant margin while maintaining similar or greater data return capability.

One of the several technical challenges that could hinder the development of laser communications is that the smaller transmit beamwidth imposes stringent demands on the pointing accuracy of the instrument. Inaccurate beam pointing can result in significant signal fades at the receiving site and a severely degraded system performance. As a result, the laser transmitter on board the spacecraft must be capable of tracking the receiving station to maintain small residual pointing error compared with the transmit beamwidth. For deep space applications this requires pointing the transmit laser beam to within $1/20^{th}$ to $1/30^{th}$ pixel accuracy based on the 1024 by 1024 focal plane array (FPA) [4]. Furthermore at distances exceeding 1 AU (Astronomical Unit) from the Earth, a tracking method based on the Sun-illuminated Earth images has been favored over an active laser beacon primarily due to requirement for high laser powers. To successfully track a Sun-lit Earth image, an accurate spatial acquisition must be preceded to provide conversion from tracking output to actual transceiver locations.

Two algorithms based on single snapshot of Earth have been investigated for acquisition using either image correlation [1] or edge detection [2]. The correlation method works by correlating the detected Earth image with a template image generated from apriori knowledge of the Earth image. The result is an estimate between the template image and the detected image. Edge detection method tries to extract high contrast edges such as Earth limb resulting from the dark space background and the Sun illuminated Earth surface. The estimated orientation of Earth and known radius can be used to compute the center of Earth. The offset from the center of Earth gives the receiver location. Simulation results on both algorithms showed that an error of less than $1/10^{th}$ of the pixel was difficult to achieve [3].

This paper describes an alternative scheme to meet the pointing requirement based on multiple images that are sequentially scanned in two, orthogonal directions. Estimating two sets of edges in orthogonal directions gives sufficient information for deriving the center of Earth. The receiver location can then be easily computed from the known offset. The Earth images are assumed to be taken with scanning steps smaller than a pixel size. This can be accomplished using the state-of-the-art Fine Steering Mirror (FSM) which has a very fine resolution even at high speed. The step size and performance of the algorithm will determine the acquisition accuracy. The scanned image sequences represent the image intensity profile convolved with the optics point spread function (PSF). As the step size becomes smaller, the intensity profile becomes closer to the true image intensity profile. This comprises more information than one snapshot of the image, thus produces high-resolution images. The idea of using multiple frames of images to increase the resolution has already been explored in other application areas including image restoration [8] and resolution enhancement of digital video [6]. The image shift can be either uniform [8] or non-uniform [6]. Other technique was also suggested, which uses different defocusing to generate multiple images [7].

Our algorithm represents an extension of the edge detection scheme, which uses the first derivative rather than a non-zero threshold value to determine the edges of the Earth image. This approach is also less sensitive to the albedo variations since the edge is not determined by the threshold value of intensity. Once the edges are determined at one direction, this procedure is applied to the orthogonal direction. The two sets of edges are used to determine the center of Earth and the transceiver location.

2. Method

2.1 Subpixel scanning

A straightforward method to improve acquisition accuracy is to reduce pixel size of the detector. However, the size of the detector pixel cannot indefinitely be reduced to improve acquisition accuracy for the basic reason that a minimum energy larger than noise level must be collected to meet the required accuracy. Another approach is to reduce the field of view of the telescope, which gives same effects. This, however, cannot be arbitrarily reduced due to the fact that the telescope FOV should be large enough to cover the acquisition FOV.

In this study, we take an alternative approach to improve acquisition accuracy using multiple, sequential images to increase resolution. Sequential images can be obtained through mechanical scanning in sub-pixel resolution using the state-of-the-art technology fast steering mirrors (FSM). As other similar methods, the step size is assumed to be equal during the entire scanning period.

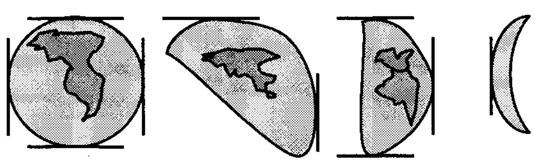
The effect of subpixel scanning is equivalent to higher spatial sampling rates. This increases the spatial frequencies in the sampled image. Therefore, the image data without subpixel scanning is the subset of that of subpixel scanning. As the spatial sampling rate increases (or the step size of scanning decreases), the accuracy of the detected edges is expected to improve.

2.2 **Edge detection**

We used gradient approach for edge detection, which is inherently sensitive to noise [9]. To make it less sensitive, low pass filtering was applied to smooth the data [10]. The edges in the image correspond to inflection points of the smoothed image. These inflection points in turn correspond to local maxima of the absolute value of the first derivative or, equivalently, to the zero crossings of the second derivative of the smoothed image. In our case, both methods worked equally well due to high contrast between bright Earth surface and dark space background. More sophicated edge detection scheme such as moment-based edge operator [9] can be used to improve the accuracy further.

2.3 **Application to the spatial acquisition**

The Earth image varies due to albedo and SEP (Sun-Earth-Probe) angles. Therefore, the number of detectable edges is limited. For a full Earth image, two sets of edges in orthogonal directions are available to derive the center of Earth (figure 1a). For a half Earth image, two or three edges can be detected (figure 1b & c). For crescent Earth (figure 1d), only one edge with additional information on the Earth can be used to derive the center of Earth.



(a) (b) (c) (d)

Figure 1. Earth images at various SEP angles and the detectable edges (solid lines)

3. **Simulation results**

Simulation procedure is shown in figure 2.

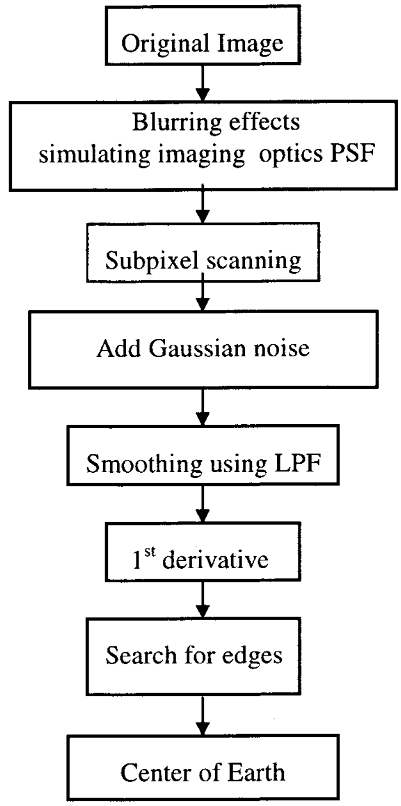


Figure 2. Simulation procedure

Three Earth images taken at various SEP (Sun-Earth-Probe) angles were used in simulations. The size of original images, Gaussian PSF, and blurred image are 60x60, 21x21, and 80x80, respectively. The size of focused image on FPA is 4x4 which is the expected size of Earth seen at the distance of Jupiter (4 – 6AU) given 7mrad telescope FOV and 1024x1024 FPA [4]. Three step sizes were used (1/2, 1/5th , 1/10th pixel). The direction of scanning is from top to bottom on second or third column of 4x4 images. The assumed noise level (Gaussian noise) is equivalent to quantization noise due to the resolution of 6 bits which is lower than that of most spacecraft imaging system. The errors from the estimates of the two edges and the center of Earth in vertical axis are shown in tables 1, 2, and 3. The results show that step size of ½ pixel does not meet our acquisition accuracy of 1/20th pixel. Step sizes of both 1/5th pixel and 1/10th pixel meet our requirement with 1/40th pixel accuracy. The intensity profiles shown in figures 3d, 4d, and 5d were preprocessed with low pass filtering. Given the added noise, a total of 50 runs were performed for each Earth image and the results were identical showing robustness against noise.

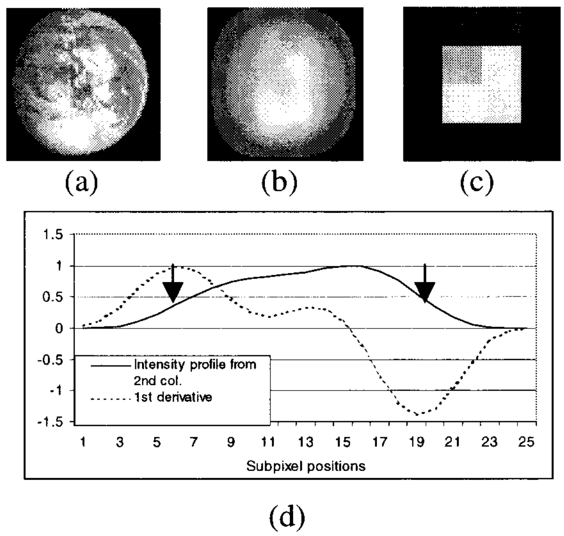


Figure 3. Earth image at SEP angle less than 90 degrees: (a) original image (b) blurred image (c) focused image on 4x4 FPA (d) Intensity profiles from subpixel scanning (scan step size of 1/5 pixel) and edges (arrows) from 1st derivative

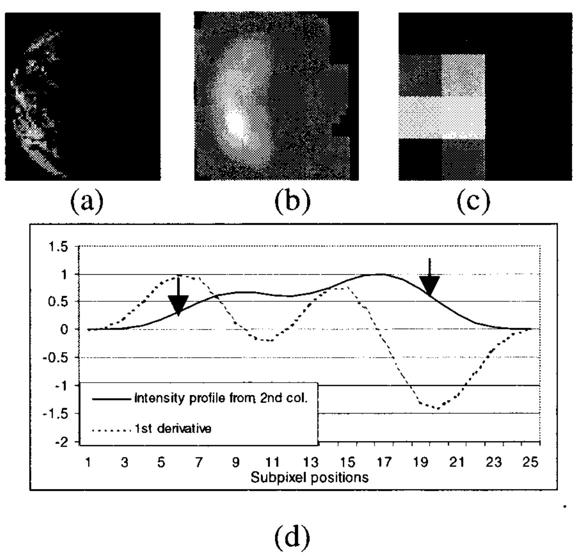


Figure 4. Earth image at SEP angle greater than 90 degrees: (a) original image (b) blurred image (c) focused image on 4x4 FPA (d) Intensity profiles from subpixel scanning (scan step size of 1/5 pixel) and edges (arrows) from 1st derivative

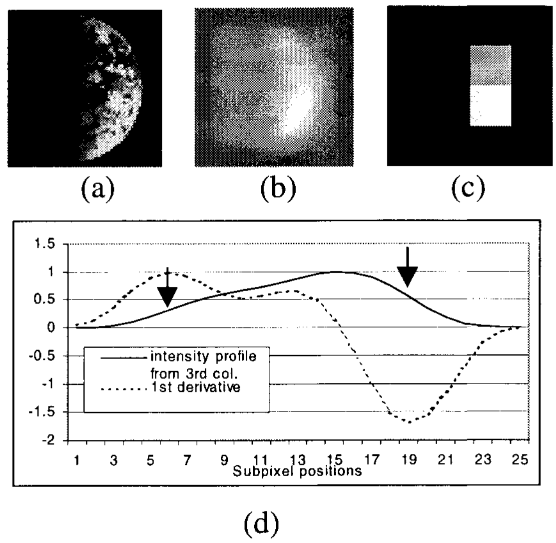


Figure 5. Earth image at SEP angle greater than 90 degrees: (a) original image (b) blurred image (c) focused image on 4x4 FPA (d) Intensity profiles from subpixel scanning (scan step size of 1/5 pixel) and edges (arrows) from 1st derivative

Scan step size (pixel)	**Edge 1**	**Edge 2**	**Center of Earth**
1/2	0.45	0.1	0.275
1/5	0.15	0.1	0.025
1/10	0.15	0.1	0.025

Table 1. Errors in estimation of two edges and the center of Earth (figure 2) for three different scan step sizes (errors in pixel).

Scan step size (pixel)	**Edge 1**	**Edge 2**	**Center of Earth**
1/2	0.3	0.05	0.175
1/5	0	0.05	0.025
1/10	0	0.05	0.025

Table 2. Errors in estimation of two edges and the center of Earth (figure 3) for three different scan step sizes (errors in pixel).

Scan step size (pixel)	Edge 1	Edge 2	Center of Earth
1/2	0.15	0.1	0.025
1/5	0.05	0.1	0.025
1/10	0.05	0.1	0.025

Table 3. Errors in estimation of two edges and the center of Earth (figure 4) for three different scan step sizes (errors in pixel).

4. Conclusion

We have presented a new spatial acquisition algorithm using subpixel image scanning. Our simulation results show that the acquisition accuracy on the order of 1/40th pixel width can be achieved consistently using step sizes of 1/5th and 1/10th pixel. The results also show that the added noise does not deteriorate the acquisition accuracy demonstrating that the new algorithm is quite robust against noise.

5. Acknowledgement

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